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4. Design and Evaluation of Clothing for Protection from Heat Stress: An Overview

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1. Introduction

The human body compensates well for moderate climatic heat stress, but artificial environments often block or overwhelm physiological defence mechanisms. Examples from industry include combinations of high air temperature and extreme radiant load in smelters, foundries and glassworks; elevated wet bulb temperatures which cause problems in very deep mines, ship engine compartments and textile drying rooms. Workers cannot tolerate such environments indefinitely without some relief from thermal stress.

Another source of heat stress is clothing worn for protection from nonthermal hazards. Examples are the sealed, pressurized suits or other highly specialized protective ensembles which are required to preserve life in hostile environments such as toxic, radioactive, or hypoxic atmospheres, at altitude and for extravehicular activity in space. In these cases the clothing tends to trap metabolic heat, and thermal balance is possible only in the coolest environments.

Thermoprotective clothing is defined as a wearable system that ameliorates unacceptable heat stress. Since such systems carry significant ergonomic and economic penalties, a 'brute force' approach is rarely feasible. It is therefore necessary to consider the many factors which determine the nature of the heat stress and to tailor design and testing to the specific problem at hand. Steps in the process include setting appropriate thermal goals, analysing the heat stress problem, selecting protective measures and testing candidate systems.

2. Setting thermal goals

Although we would like to keep workers continuously comfortable, that is not always possible or even necessary. Therefore, an important

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step in system design is to determine the degree of thermal stress which is acceptable for a given situation. Four potential goals can be distinguished.

Comfort. A comfortable microclimate is desirable where the worker is expected to perform critical mental tasks. In some cases it may be desirable not only to prevent sweating but also to minimize cutaneous vasodilation with its attendant shift in cardiac output.

Long-term health maintenance. The goal here is prevention of cumulative fatigue and morbidity which would adversely affect productivity. This goal is primarily of concern where a prolonged, stressful exposure must be repeated on a daily basis. An upper limit of 38°C core temperature is often used in industry for this purpose.

Core temperature tolerance. Excessive heat storage raises core temperature to levels likely to produce physical collapse. An upper limit of 39·5°C rectal temperature is often used for acute heat exposures in the laboratory.

Skin temperature control. Radiant heating can rapidly raise skin temperature to the pain threshold, about 45°C.

3. The heat stress triad

Heat stress problems generally require analysis in terms of three possible contributing factors: work rate, environment and clothing. Unacceptable heat stress may be produced by one of these factors or by two or three of them in combination, as illustrated in Figure 4.1.

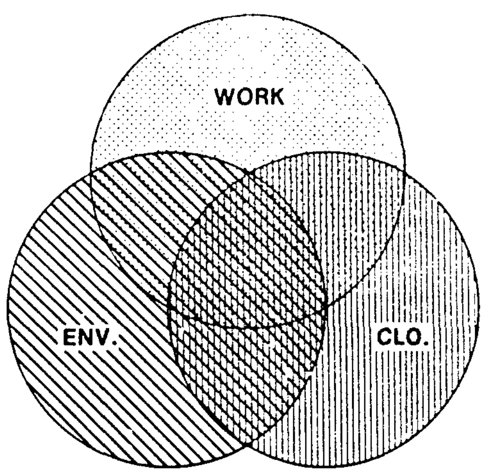

Figure 4.1. The heat stress triad, consisting of work, environment and clothing.

The rise in core temperature which normally accompanies sustained work is not in itself a threat, but problems develop when environmental conditions and/or clothing prevent dissipation of excess metabolic heat and thus interfere with achievement of a tolerable steady-state condition (Leithead and Lind, 1964).

Whenever possible, design of thermoprotective systems should include options for lowering metabolic heat production. Possibilities include providing mechanical aids, dividing the work among more people, or scheduling regular rest breaks. A marginal situation may also be improved by implementing controls on the physical fitness and heat acclimatization of workers, so that the existing stress represents a small percentage of individual capacity.

Mechanisms for heat exchange between body and environment include conduction, convection, radiation and evaporation. Planning for intervention in heat stress requires a clear understanding of the contribution of each of these types of heat transfer. Excellent reviews are available in this area (Goldman, 1978, Kerslake, 1972, Leithead and Lind, 1964).

Clothing interferes with heat transfer between the skin and the environment, creating a complicated series of thermal exchanges (Figure 4.2). Characterization of clothing requires determination of its thermal insulation value, its resistance to transmission of water vapour, and its wind permeability. The exchange of air or 'pumping' associated with body movements is also a major factor.

In the case of clothing which is impermeable to water vapour, thermal equilibrium is possible only in environments cool enough to remove the necessary heat through the suit by a combination of conduction and convection. Heat transfer from the skin to the suit may

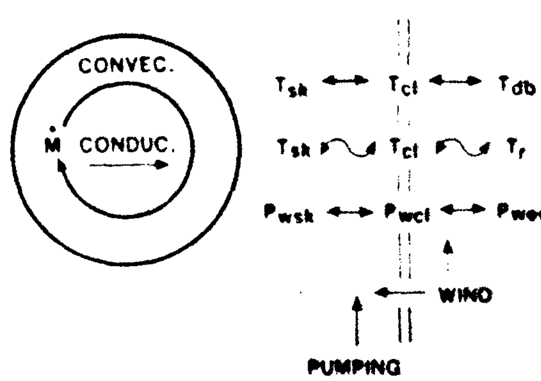

Figure 4.2 A simplified diagram of heat exchange between body and environment with an intervening layer of clothing. Major symbols: M = metabolic heat production, T = temperature, P = vapour pressure. Subscripts: sk = skin, w = water, db = dry bulb, r = mean radiant, env = environmental

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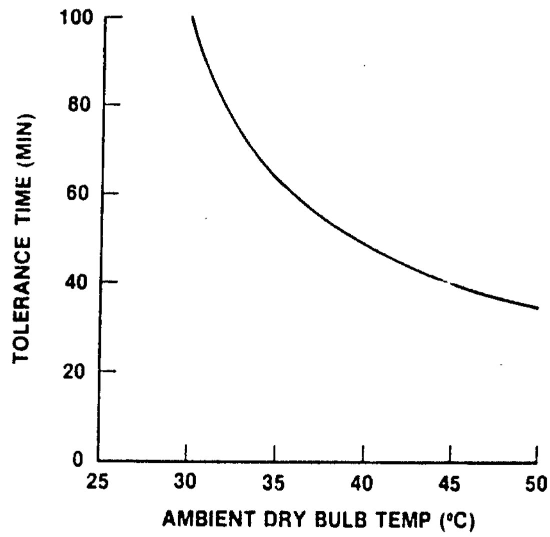

Figure 4.3. Tolerance time limits for men wearing impermeable suits and working at $\dot{V}_{O_2}$ = 1 l min^{-1} at various environmental temperatures. After Shvartz and Benor (1971).

involve evaporation of sweat from the skin followed by condensation on the cool inner surface of the suit (Crockford, 1968). Limits on human tolerance time for moderate work in impermeable suits are indicated in Figure 4.3.

4. *Possible solutions*

Thermoprotective clothing can be divided into two major categories, passive and active, the latter having moving parts and requiring attachment to an energy source.

Passive systems

Conventional clothing offers some protection from external heat loads. For instance, the desert dweller's burnoose reduces solar heat load without blocking air flow. Extreme radiant heating may be counteracted by reflective materials lined with heavy insulation; a good example is the firefighter's 'bunker', a garment made of aluminized asbestos (now Kevlar) and used for work near high-temperature fires.

Phase change of water or another substance can be used for passive cooling. An example is the ice vest, a garment which contains pockets of frozen water. The ice vest cools the microclimate through melting

the ice and warming the resulting water (Van Rensburg *et al.*, 1972). The very low starting temperature of the heat sink means that the vest must be worn over an insulation garment to prevent skin chilling. It is also advantageous to provide external insulation so that less heat is absorbed directly from the environment. Vests containing 4.5 kg of ice are used in the South African gold mines to provide [illegible] work in an environment with a wet bulb temperature of 33–36 °C (Strydom, 1974).

Another application of phase change is the evaporation of water from a wettable layer worn outside an impermeable suit, a technique which requires the rather paradoxical combination of large quantities of water and an environment dry enough to accept water vapour.

Active systems

These systems use an external heat sink to cool a fluid (usually air or water) which is then pumped through the clothing system to provide microclimate conditioning (Figure 4.4). The heat picked up by the cooling loop may come from metabolism and from the environment (Fonseca, 1976; Shvartz, 1972). External heat sinks can be based on many different mechanisms, some of which are listed in Table 4.1.

Design of active cooling systems should include a failure mode analysis and, specifically, consideration of consequences if cooling is

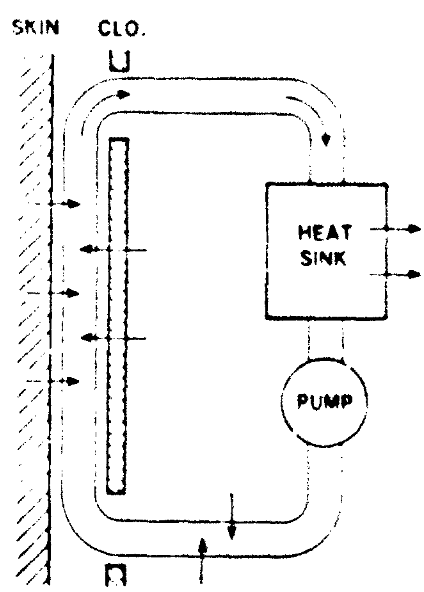

Figure 4.4 Diagram of an active cooling system. The arrows indicate movement of heat from the body to the fluid stream and thence to the heat sink, which dumps it into the environment

Table 4.1 Potential heat sinks for the air-ventilated suit (AVS) and for the liquid-conditioned garment (LCG).

Heat sink	AVS	LCG
Ambient air	X	
Compressed air ([illegible]tex)	X	
Evaporation (wate[illegible] other)	X	
Super-cold liquid (air, other)	X	
Vapour cycle refrigration	X	X
Thermoelectric device	X	X
Ice (water, CO_2)		X

interrupted. Thus, the cooling garment should be included in measurements of insulation and permeability for the entire clothing ensemble.

Air-ventilated suit (AVS)

The AVS is supplied with a flow of gas which is distributed over the body by a system of ducts or by a spacer garment; in either case, the air paths must be structured to maintain patency. For permeable suits, air may exit the clothing through the fabric and at openings such as neck, wrist and ankles. Impermeable suits generally have one-way valves to dump air to the environment.

Air cools the body by convection and/or evaporation. Since these cooling mechanisms are under physiological control, adequate air conditioning of the microclimate should allow the body to fine tune heat exchange in the normal manner.

Factors which determine AVS performance include the temperature and humidity of the air supply, mass flow and the effective surface area available for heat exchange. Convective cooling is a relatively weak mechanism because the specific heat of air is low. Theoretically, cooling could be improved by supplying extremely cold air, but in practice inlet temperature must remain above freezing to prevent discomfort from local chill near air vents and also to avoid condensation and freezing of water in piping and valves. Evaporation is a strong cooling mechanism, removing 0·58 kcal g^{-1} of water evaporated, but the person must first become hot enough to sweat, and therefore experiences continuous discomfort and eventual dehydration. In any case, air flow through the suit is limited by problems with noise, wind and a tendency for the suit to develop positive pressure and inflate to awkward bulkiness.

The AVS may be combined with either permeable or impermeable clothing and may cover the entire body or only part of it, as in a ventilated jacket or hood. Air cooling has been used with some success for fliers wearing anti-exposure suits and recently for army tank crews

operating in hot weather, both of which involve limited physical work. The AVS is also used in industry for hot trades.

Ventilation was inadequate as a cooling mechanism for suited astronauts performing extra-vehicular work, but a special factor was the low barometric pressure in the suit which significantly reduces convective thermal exchange at the same time that it enhances evaporative capacity.

Where an extremely hot environment allows wear of permeable clothing, Crockford *et al.* (1974) showed that there are advantages to using radial air flow through the material to provide 'dynamic insulation' which removes impinging heat before it reaches the body (Figure 4.5). This work indicates that this is a more efficient use of the conditioned air than is the conventional axial flow pattern.

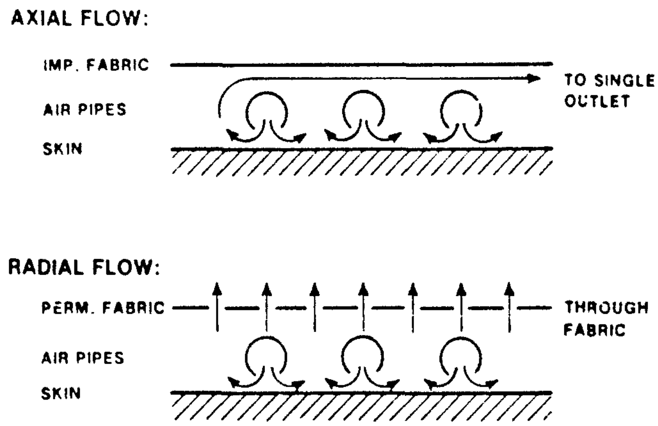

Figure 4.5. Diagram of ventilating air flow in axial and radial patterns. The latter can be used only with air-permeable materials.

Selection of an air source is an important aspect of AVS design. Portable ventilation systems exist, but they weigh 6–8 kg, provide only about 30 l min^{-1} of air at ambient conditions, and the work of carrying the equipment negates a significant portion of the cooling provided. A portable, cooled system based on liquid air has also been demonstrated (Gleeson and Pisani, 1967). Nevertheless, tethering is the usual means of supplying air despite the inevitable limitations on movement. Piping for chilled air must be insulated and kept short to minimize environmental heat pick-up. Longer lines can be used to connect compressed air to a cooling device co-located with the subject. The most common device for this application is the vortex tube, which uses the energy of expansion to divide the air flow into separate streams of cold and hot air (Brown, 1965; Van Patten and Gaudio, 1969).

Liquid-conditioned garment (LCG)

The LCG is worn next to the skin or over thin underwear and contains small-diameter tubing or heat-sealed vinyl patches through which liquid circulates to provide convective cooling. Several review articles on LCGs have appeared (Harrison and Belyavin, 1978; Midwest Research Institute, 1975; Nunneley, 1970).

The superior cooling capacity of water means that a liquid-based system requires much lower mass flow and less pumping energy than does a system using air, and therefore has a lower overall weight. Unlike the AVS, LCG cooling is relatively independent of fluid flow but is highly sensitive to inlet temperature (Harrison and Belyavin, 1978). Experiments have demonstrated that a full-coverage tubing suit connected to an unlimited heat sink can keep a subject comfortable regardless of environment (Shvartz and Benor, 1971) or work load (Webb and Annis, 1968). The design question then becomes one of tailoring the garment and the heat sink to the particular application.

Disadvantages of the LCG include the need for a reasonably close fit on the subject and possible ill-effects should the liquid loop spring a leak. Humid environments will produce condensation on the LCG, thus contributing to dampness of the clothing and stealing some of the cooling capacity of the system. The patch type of LCG forms a vapour barrier which could cause problems it cooling were cut off.

Again, heat sinks may be either portable or fixed. Current US space suits incorporate a back-mounted heat sink which sublimates ice to vacuum. Earthbound portable systems use melting ice as the external heat sink, but the weight of the system, the need for frequent replacement of ice, and the logistic consequences of this all conspire to limit applicability. Miniature vapour-cycle refrigerators powered by batteries or gasoline engines are currently under development and would improve the logistics of the system.

Tethering the LCG to a heat sink is best adapted to seated operators or those doing physically circumscribed work. An alternative application is intermittent cooling, under study in our laboratory, in which the worker wears the LCG continuously but is attached to the heat sink only during rest breaks. Attempts to use this technique with air cooling have met with little success because core temperature simply remains elevated during the break, but the stronger cooling offered by an LCG offers some promise for enhanced thermal recovery.

The great cooling power of LCGs means that it may not be necessary to cool the entire body, particularly if work rate is low. In that case the area covered by the garment and the size of the external heat sink must be adapted to the particular heat stress condition.

The powerful cooling offered by the LCG brings with it the potential

problem of overcooling, with associated discomfort and/or paradoxical heat storage. While subjects can learn to control inlet temperature in an appropriate manner, automatic systems have been demonstrated in which inlet temperature is controlled with reference to some combination of garment temperature, skin temperature or heart rate (Kuznetz, 1980).

5. Some special considerations

Regional cooling

Various body regions differ in their capacity for delivering heat to a cooled garment. Relevant characteristics include peak conductance, vasoconstriction threshold, preferred temperature and subjective comfort weighting (Crawshaw *et al.*, 1975). The face, hands and feet show a strong vasoconstrictive response to cooling, combined with subjective awareness of discomfort; these areas are therefore not only inconvenient but physiologically unsuitable for systemic cooling. In contrast, the head and neck do not vasoconstrict until very cold and are well suited to cooling (Nunneley *et al.*, 1971). Various body areas can thus be ranked according to the efficiency of cooling those sites (Shvartz, 1972).

Skin temperature normally varies over the body, and comfort is associated with a temperature gradient of several degrees from the cooler extremities to the warmer torso and head. This pattern can be accommodated by delivering a cooling medium (air or water) to the extremities and collecting it centrally, a pattern which should be reversed in garments used for heating.

Effects of physical fitness

A high level of aerobic fitness may provide improved tolerance for work-heat stress and may also enhance the effectiveness of artificial cooling. For the fit individual, a given task uses a lower fraction of work capacity and therefore produces a lower equilibrium rectal temperature (T_{re}), a greater heart rate reserve and less cumulative fatigue. The activities which induce and maintain a high level of fitness also involve partial acclimation to heat stress, with accompanying changes in sweat production, lowering of sweat electrolyte content, and increased plasma volume. All of these may assist thermoregulation in ventilated systems.

We find that LCGs also appear to be more effective in very fit individuals. Although their leanness could be a factor, skinfold thickness should not greatly alter heat dissipation. Nor should improved

sweating play a major role in heavily clothed persons. We speculate that in fit individuals work-induced hyperthermia produces a more active cardiovascular response including enhanced blood flow to the skin, thus improving heat transport from core to LCG.

Paradoxical effects

Early work on artificial cooling produced a strong debate on whether head cooling might 'fool the hypothalamus' into inappropriate suppression of sweating (McCaffrey, 1975). The fact that head cooling lowers tympanic temperature was cited early on as evidence for a direct effect on brain temperature, but it is now known that the ear canal receives part of its blood supply from the face and is therefore affected by external temperatures (McCaffrey, 1975; Nunneley *et al.*, 1971). Other experiments indicate that the body somehow regulates sweating according to net heat load, even in the presence of strong regional temperature differences (Nunneley *et al.*, 1971; Williams and Chambers, 1971; Williams and Shitzer, 1974). Head cooling does strongly influence comfort and might therefore impair a subject's judgement regarding the severity of heat stress and the extent of physiological reserves.

Heat stress and mask intolerance

Some workers must wear respirators during heat stress, for example, firefighters and mine rescue personnel. Several studies show that work in heat causes a high incidence of dyspnoea and mask intolerance even among highly trained personnel. This phenomenon may reflect hyperventilation, which normally develops as core temperature rises above 38°C, or may involve some other mechanism(s) (Petersen and Vejby-Christensen, 1973).

6. *Evaluation of thermal protection*

Thermoprotective systems can be evaluated in a number of ways, including the guarded hot plate, heated manikins, computer models, chamber simulations and field trials. Each has its own limitations and advantages, and it is necessary to select the appropriate step or series of steps to produce the desired information at the lowest possible cost in time, money and risk to human subjects. Often there is complex, iterative interaction among one or more of these techniques. In some cases, alternate systems can be compared, as in an RAF study of air and water cooling techniques for pilots (Allan *et al.*, 1971).

Final selection of thermoprotective systems requires consideration of several aspects of their performance.

1. Effectiveness. Whether the proposed solution produces the desired thermal result, reliably reaching the goal selected earlier.
2. Efficiency. Assurance that the final system is the best thermal answer in physical and physiological terms.
3. Compatibility. Whether the system will fit into the workplace without adversely affecting productivity.
4. Practicality. Assurance that the solution will work, including considerations of logistics, ruggedness and repairability.
5. Cost. Consideration of economic consequences including both initial investment and upkeep.

In conclusion, the design and evaluation of thermoprotective systems clearly involve a mixture of skills and expertise ranging from physics and computer programming through ergonomics and physiology to engineering and cost analysis. Technological improvement is still possible in many areas.

References

Allan, J.R., Allnutt, M.F., Beeny, M., Hanson, R. de G., Morrison, J., Needham, R.W.J., Robertson, D.G. and Short, B., 1971, A laboratory comparison of three methods of personal condition. *RAF Institute of Aviation Medicine, Report No. FPRC/1307.*

Brown, J.R., 1965, Impermeable clothing and heat stress. *Med. Serv. J. Canada*, **21**, 518–532.

Crawshaw, L.I., Nadel, E.R., Stolwijk, J.A.J. and Stamford, B.A., 1975, Effect of local cooling on sweating rate and cold sensation. *Pflugers Arch.*, **354**, 19–27.

Crockford, G.W., 1968, Industrial pressurized suits. *Ann. Occup. Hyg.*, **11**, 357–365.

Crockford, G.W. and Awad El Karim, M.A., 1974, Assessment of a dynamically-insulated heat-protective clothing assembly. *Ann. Occup. Hyg.*, **17**, 111–121.

Fonseca, G.F., 1976, Effectiveness of four water-cooled undergarments and a water-cooled cap in reducing heat stress. *Aviat. Space Environ. Med.*, **47**, 1159–1164.

Gleeson, J.P. and Pisani, J.F., 1967, A cooling system for impermeable clothing. *Brit. J. Industr. Med.*, **24**, 213–219.

Goldman, R.F., 1978, Prediction of human heat tolerance. In *Environmental Stress*, edited by S.J. Folinsbee (New York: Academic Press).

Harrison, M.H. and Belyavin, A.J. 1978, Operational characteristics of liquid-conditioned suits. *Aviat. Space Environ. Med.*, **49**, 994–1003.

Kerslake, D.McK., 1972, *Stress of Hot Environments* (Cambridge: Cambridge University Press).

Kuznetz, L.H., 1980, Automatic control of human thermal comfort by a liquid-cooled garment. *Biomech. Eng.*, **102**, 155–161.

Leithead, C.S. and Lind, A.R., 1964, *Heat Stress and Heat Disorders* (Philadelphia: Lea & Febiger).

McCaffrey, V., Davis, F.A., Geis, G.S., Chung, M. and Wurster, D., 1975, Effect of isolated head heating and cooling on sweating in man. *Aerospace Med.*, **46**, 1353–1357.

Midwest Research Institute, 1975, *Liquid Cooled Garments*. NASA CR-2509, 51 pp.

Nunneley, S.A., 1970, Water cooled garments: a review. *Space Life Sci.*, **2**, 335–360.

Nunneley, S.A., Troutman, S.J., Jr and Webb, P., 1971, Head cooling in work and heat stress. *Aerospace Med.*, **42**, 64–68.

Petersen, E.S. and Vejby-Christensen, H., 1973, Effect of body temperature on steady state ventilation and metabolism in exercise. *Acta Physiol. Scand.*, **89**, 342–351.

Shvartz, E., 1972, Efficiency and effectiveness of different water cooled suits—a review. *Aviat. Space Environ. Med.*, **43**, 488–491.

Shvartz, E. and Benor, D., 1971, Total body cooling in warm environments. *J. Appl. Physiol.*, **31**, 24–27.

Strydom, N.B., Mitchell, D., Van Rensburg, A.J. and Van Graan, M., 1974, Design, construction, and use of a practical ice-jacket for miners. *J. S. Afr. Inst. Min. Metall.*, **74**, 5 pp.

Van Patten, E. and Gaudio, R., Jr, 1969, Vortex tube as a thermal protective device. *Aerospace Med.*, **40**, 289–292.

Van Rensburg, A.J., Mitchell, D., Van Der Walt, W.H. and Strydom, N.B., 1972, Physiological reactions of men using microclimate cooling in hot humid environments. *Brit. J. Industr. Med.*, **29**, 387–393.

Williams, A. and Chambers, A.B., 1971, Effect of neck warming and cooling on thermal comfort. *Second Conference on Portable Life Support Systems*. NASA SP-302.

Williams, A.B. and Shitzer, A., 1974, Modular liquid-cooled helmet liner for thermal comfort. *Aerospace Med.*, **45**, 1030–1036.

Webb, P. and Annis, J.F., 1968, Cooling required to suppress sweating during work. *J. Appl. Physiol.*, **25**, 489–493.